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DIGITAL VIDEO: number of bits per sample required for reference coding of luminance and colour-difference signals

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DIGITAL VIDEO: NUMBER OF BITS PER SAMPLE REQUIRED FOR REFERENCE CODING OF LUMINANCE AND COLOUR-DIFFERENCE SIGNALS

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Summary

Work has been undertaken to provide the basic parameters of a reference pulse code modulation (p.c.m.) system intended as a standard of comparison for any digital system designed to transmit high-quality colour television signals. It uses separate coding of the luminance and two colour-difference components (Y, U and V) of a colour television signal. Such a system is unlikely to need a lower bit rate than a p.c.m. system coding a composite PAL signal, but it would have the advantage that it would be independent of the type of colour-coding system employed for the associated analogue signal.

The number of bits per sample required for each of the three component signals Y, U and V was estimated using two different theoretical approaches. Firstly, the quantising accuracy was made to correspond to the random noise allowable on a hypothetical reference analogue circuit. Secondly, the quantising accuracy required was determined by referring to known 'just noticeable differences' in the luminance and chromaticity of the display. Subjective tests were also carried out using both critical test signals and signals from a slide scanner representative of typical pictures.

A comparison is made between the various results obtained and it is concluded that for normal high-grade picture sources seven bits per sample are required for each of the three component signals; this conclusion applies whether or not a dither signal is added prior to quantising. It is assumed that the signals may have to pass through up to four coded in tandem.

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DIGITAL VIDEO: NUMBER OF BITS PER SAMPLE REQUIRED FOR REFERENCE CODING OF LUMINANCE AND COLOUR-DIFFERENCE SIGNALS

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1. Introduction

The digital transmission of colour television signals employing separate coding of the luminance (Y') and colour-difference (U' and V') signals would have certain advantages. Where transcoding is required between different colour transmission systems (such as PAL and SECAM) it could represent an intermediate stage. The total bit rate might exceed that of a digitally coded composite colour signal but, if the component signals could be derived from the primary *RGB* signals, the pictures transmitted would be free from certain defects associated with subcarried-coded signals such as 'cross-colour' effects.

To contribute to a study by Working Party C of the EBU, work was undertaken to provide the parameter values of a 'reference codec' employing separate digital coding of the luminance and colour-difference signals. Such a reference system, based on pulse-code-modulation (p.c.m.) coding of the signals is useful to set a practical standard of comparison for any transmission system (including the more advanced differential p.c.m. systems) that may be developed for the transmission or processing of high-grade pictures. The parameters of interest are the sampling frequencies and the number of bits per sample required for each of the three component signals (Y', U' and V'); it is assumed that each signal would be uniformly quantised.

The word described in this report concentrated on the specification of the number of bits per sample required in the reference codec; further work would be needed to determine the values of the required sampling frequencies.

2. Analysis

This Section first outlines the form of a digital transmission system using separate coding of the luminance and colour-difference signals. Theoretical estimates of the required number of bits per sample are then given, using two different derivations:

(a) The quantising noise is equated to the maximum allowable random noise level in the luminance and chrominance bands of a hypothetical reference analogue circuit.

(b) The maximum allowable step between quantising levels which would just avoid perceptible spurious boundaries (contouring) on the displayed picture is calculated.

2.1. Fundamentals of colour-component coding

The general form of a transmission system employing separate coding of the luminance and colour-difference signals is shown in Fig. 1. Y' is the transmitted luminance signals; V' and U' are the transmitted colour-difference signals and correspond to the (R-Y) and (B-Y) components respectively of a television signal.

The equations describing the system are outlined in the Appendix, Section 7.1; they correspond to the System I television parameter values.

Some facts pertinent to the present investigation are as follows:

(i) Gamma-correction is applied to the *RGB* signals prior to transmissions; the value of gamma (γ) is taken to be 2·5.

(ii) The values of the *RGB* signals, whether gamma-corrected or not, and not including synchronising pulses, are taken to occupy the range 0 to 1; this is also the range of the Y' signal. Hence the V' and U' signals have peak-to-peak ranges of 1·402 and 1·772 respectively.

(iii) The bandwidth of the luminance signal is taken to be 5·5 MHz; both colour-difference signals have bandwidths in the region of 1·5 MHz, although components above that frequency are not sharply suppressed in conventional colour-coding systems.

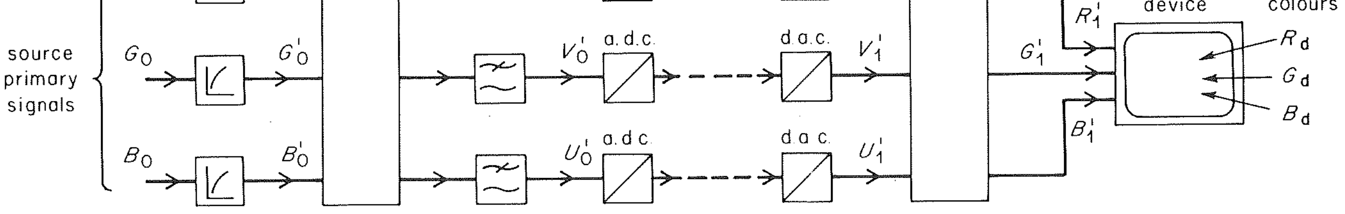

Fig. 1 - Reference Codec: General form of transmission system

Subjective effects are assumed to be related proportionally to fractional changes in the luminance (L) of a display[1] and to changes in a pair of chromaticity co-ordinates derived from the primary colours RGB by the following equations:

$$u = {}^{X}/Z$$

and $$v = {}^{L}/Z$$

where $$X = 0{\cdot}406R + 0{\cdot}116G + 0{\cdot}167B$$

$$Z = 0{\cdot}850R + 1{\cdot}626G + 0{\cdot}910B$$

and $$L = 0{\cdot}299R + 0{\cdot}587G + 0{\cdot}114B$$

These are the 1960 set of chromaticity coordinates; they are used because equally perceptible differences in chromaticity roughly correspond to equal distances $\sqrt{(\Delta u)^2 + (\Delta v)^2}$ in the (u, v) plane. This aspect is enlarged in Section 2.3.

In most of this report CCIR viewing conditions[2] are assumed. These may be summarised as follows:

(i) The maximum luminance of the display device equals 70 cd/m^2.

(ii) The luminance produced by the display device under zero signal conditions equal 1% of maximum.

(iii) The ambient illumination (with the display device switched off) is less than 2% of the maximum luminance.
(In this report the amount of ambient illumination is assumed to be 1% of the maximum luminance).

2.2. Random-noise equivalence

One method of estimating the number of bits per sample required to describe the component signals is to calculate the quantising accuracy which results in a noise power equal to the maximum permissible random-noise level in the luminance and chrominance bands of a hypothetical reference transmission circuit for a PAL analogue signal. The figures quoted for permissible weighted noise levels[3] are −52 dB in the luminance channel and −46 dB in the chrominance channel of a PAL signal, relative to a full luminance signal swing (black level to peak white). In the Appendix, Section 7.2, it is calculated that this is equivalent to using 5·58 bits for the gamma-corrected luminance signal Y' and 5·72 bits each for V' and U'.

Because quantising noise has a flat spectral density, any total noise power figures depend on sampling frequencies and signal bandwidths; the figures quoted above are based on sampling frequencies of 13·3 MHz for Y' and 4·43 MHz for V' and U'. The signal bandwidths are 5·5 MHz for Y' and 1·5 MHz for V' and U'. In general less bits would be required as the sampling frequency is increased, the equivalence being half a bit for a doubling of that frequency.

An equivalence between random and quantising noise is valid only when the quantising noise has a random character; as mentioned below this would not be the case if the signal were slowly varying and contouring effects became noticeable. To avoid these effects it is advantageous to 'randomise' the quantising noise by adding a 'dither' signal prior to quantising;[4] this degrades the signal-to-noise ratio slightly (by 1·5 dB) and the figures quoted above must accordingly be raised by ¼ bit, becoming 5·83 bits for Y' and 5·97 bits for V' and U', when dither is employed.

2.3. Perceptibility of contouring

On some signals contouring effects may be far more noticeable than random-type quantising noise; these effects appear in large plain areas of the picture corresponding to a slowly varying signal. By calculating the maximum value of the quantising step in each of the component signals which gives rise to a change in display luminance or chrominance not greater than a just-noticeable-difference (j.n.d.), an estimate of the number of bits per sample required to code each of the component signals may be obtained. This result will of course apply to the case where dither is not employed.

For a wide range of luminance levels, the eye responds to fractional changes in luminance (L) or equivalently to a fixed change in the logarithm of the luminance; the value of the just perceptible fractional change $\Delta L/L$ (or $\Delta \log L$) is generally taken to be 0·02.[1,5]* This quantity is known as the Fechner Fraction, or a luminance j.n.d. As mentioned in Section 2.1, chromativity variations corresponding to equal distances in the (u, v) plane are equally perceptible, a distance $\sqrt{(\Delta u)^2 + (\Delta v)^2}$ of 0·00384 being taken as a chromaticity j.n.d.[5,6]* The manner in which the display luminance and chromaticity co-ordinates are related to the component coded gamma-corrected signals is given by the equations in Section 7.3.1.

To see how the effect of small variations (such as quantising step transitions) in the component signals (Y', U', V') on the display parameters ($\log L$, u, v) vary with different colour combinations, the sensitivities of ($\log L$, u, v) with respect to (Y', U', V') were evaluated for all saturated colour combinations; the results, expressed in j.n.d. units are given in Table 1. Because the gamma power law characteristic is not regarded as being totally accurate near the origin, the source signals (R_0, G_0, B_0) were taken to have values of 0·01 in the 'off' state (e.g. red in the case of cyan).

From the table it is evident that blue is the colour most sensitive to small changes in Y' and that red and blue are, respectively, the colours most sensitive to small changes in V' and U'. The effect on those colours of perturbing

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* These figures have been experimentally determined for the case where a split field of slightly differing luminosities or chromaticities is presented to the viewer; it is reasonable to apply these figures to the evaluation of the subjective effects of contouring caused by the signals undergoing a level change corresponding to a quantising step.

TABLE 1

Sensitivities of Display Parameters to Component-Coded Signals on Various Saturated Colours, in j.n.d. Units

Colour	$\frac{\delta \log L_1}{\delta Y'}$	$\frac{\delta u_1}{\delta Y'}$	$\frac{\delta v_1}{\delta Y'}$	$\frac{\delta \log L_1}{\delta V'}$	$\frac{\delta u_1}{\delta V'}$	$\frac{\delta v_1}{\delta V'}$	$\frac{\delta \log L_1}{\delta U'}$	$\frac{\delta u_1}{\delta U'}$	$\frac{\delta v_1}{\delta U'}$
White (R,G,B)	126·0	0·0	0·0	0·0	66·3	−4·6	0·0	−1·3	−35·8
Red (R)	141·3	−61·1	−26·0	115·3	−0·7	−16·9	0·0	−7·2	−9·8
Green (G)	130·7	−5·2	11·1	−57·7	8·5	−4·6	−22·8	27·3	−5·9
Blue (B)	171·2	21·5	5·9	0·0	15·0	−0·7	109·6	0·0	−7·2
Yellow (R,G)	128·8	3·3	−1·3	0·0	90·4	−18·4	−15·3	10·4	−4·6
Magenta (R,B)	135·4	3·3	−8·5	84·3	57·2	32·5	31·1	−46·3	−37·1
Cyan (G,B)	126·8	0·7	4·6	−50·1	11·4	−18·4	0·0	13·7	−45·3

the colour difference signals is to produce a subjective luminance change ($\Delta \log L/0{\cdot}02$) which is greater than the corresponding chromaticity change ($\sqrt{(\Delta u)^2 + (\Delta v)^2}/0{\cdot}00384$); this 'cross-talk' effect is an outcome of the non-linearity introduced by gamma-correcting the R,G,B signals at source and means that luminance information is not contained exclusively in the transmitted signal, Y'.

The fractional luminance change caused by a small variation in the Y', V' or U' signals increases as the amplitude of the source signals (R,G,B or any combination of these) are reduced from their maximum values of unity. Maximum sensitivity occurs near zero signal amplitude and depends on ambient lighting.

These maximum sensitivities are calculated in Section 7.3 of the Appendix for CCIR viewing conditions; the quantising steps of Y', V' and U' which yield a luminance j.n.d., and thus the number of quantising levels required to describe each of the signals are derived.

The calculations show that, to avoid contouring effects, 336 levels (i.e. 8·4 bits) are needed to describe the luminance signal (Y'), and 172 and 171 levels (i.e. 7·4 bits each) are required to describe V' and U' respectively.

3. Subjective effects

The next stage in the investigation was testing to assess the subjective effects of using various numbers of bits per sample to represent the luminance and colour difference signals. Preliminary investigations were carried out using a variety of lighting conditions; these were followed by formal tests carried out with a number of observers under CCIR lighting conditions.

3.1. Description of signal processing

When digitising the component signals the gain and d.c. settings at the inputs to the analogue-to-digital converter (a.d.c.) were adjusted to allow the signals to just occupy the full range of the converters; the output levels were adjusted accordingly.

When assessing the subjective effect of digitising the Y', V' and U' signals to various accuracies, either the luminance signal only was quantised using monochrome pictures, or the two colour-difference signals only were quantised, the luminance signal merely being equalised in gain and delay with respect to the colour-difference signals.

The sampling frequencies were 13·3 MHz for the luminance signal and 4·43 MHz for the colour-difference signals; these figures are three times and one times the colour subcarrier frequency, respectively, and were used for instrumental convenience.

At the luminance digital-to-analogue converter (d.a.c.) output the video filter had a bandwidth of 5·5 MHz. The filters at the input to the colour-difference a.d.c.'s had bandwidths of 1·3 MHz, and those at the d.a.c. outputs had bandwidths of 1·5 MHz; these filters were not of the 'sharp-cut' variety, the attenuation of the output filters at 2·2 MHz (i.e. at half the sampling frequency) being 17 dB.

3.2. Preliminary investigation

Sawtooth (rising linear ramp) signals were found to be the most critical picture material with regard to the visibility of contouring due to quantising of any of the component signals.

Under the most critical viewing conditions possible (in which the ambient lighting and zero-signal tube current were set to zero) contouring was just noticeable on a red sawtooth, when V' was specified by 10½ bits, and on a blue sawtooth when U' was specified by 11 bits. The corresponding figure for Y' (using a white sawtooth) was 10½ bits. (The effect of representing the transmitted signal by a fractional number of bits was simulated by placing an attenuator in the signal path after the d.a.c., and increasing the attenuation until contouring became invisible.)

Next, CCIR viewing conditions were used. In this case contouring was barely visible when Y' was specified by 9 bits; contouring was visible when V' and U' were quantised to 7 bit accuracy, but not visible when 8 bits were used.

Using dither, the threshold of impairment perceptibility (under CCIR viewing conditions) was reached when all three signals were represented by between 6 and 7 bits.

3.3. Subjective tests

In addition to the test signals mentioned above, more 'typical' signals were used in the form of still pictures obtained from the output of a 35 mm colour-slide scanner.

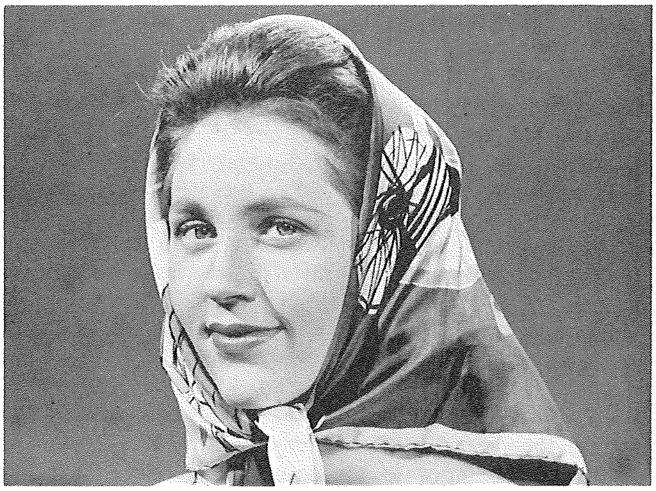
A number of observers were asked to note the impairment relative to 8 bits of separately quantising the luminance (using monochrome pictures) and then the colour-difference signals to 7, 6, 5 and 4 bits without dither; they were also asked to note the impairment relative to 8 bits of separately quantising the luminance signal to 7, 6, 5 and 4 bits and then the colour-difference signals each to 6, 5, 4 and 3 bits respectively with dither. In each case equal numbers of bits were used to represent both colour-difference signals.

The reference state of 8 bits was used for instrumental convenience during the tests; the conclusions mentioned later on in the report do indeed verify that the effects of quantising are not perceptible when 8 bits per sample are used on typical slides and with only one digital conversion.

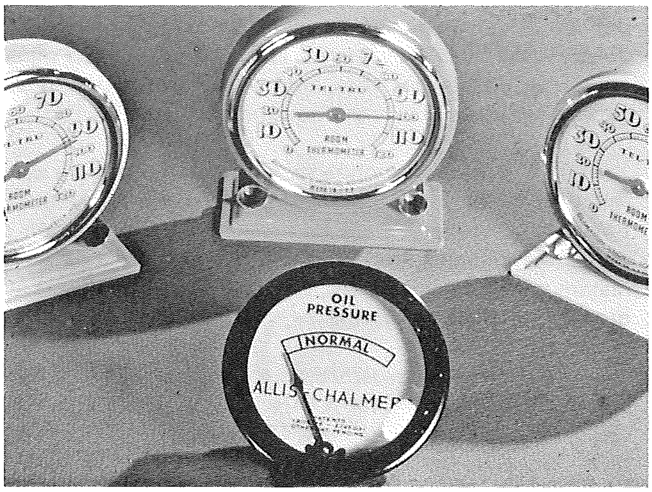
The EBU 6-point impairment scale was used:

1. Imperceptible
2. Just perceptible
3. Definitely perceptible but not disturbing
4. Somewhat objectionable
5. Definitely objectionable
6. Unusable

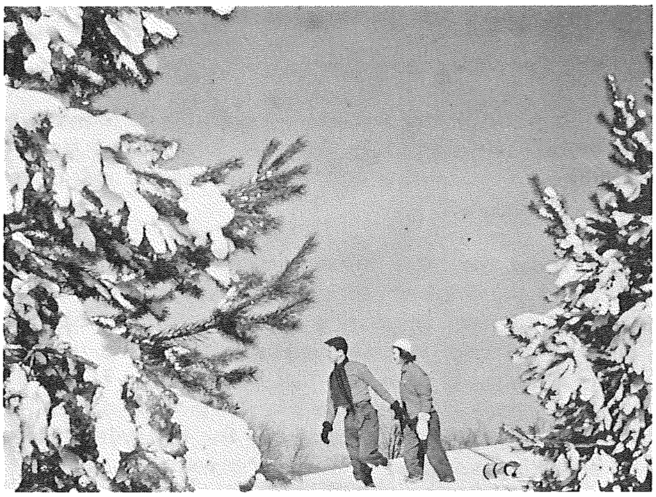
The number of observers varied between 8 and 10. To avoid any learning effects influencing the results, a random order to the test conditions was employed.



(*a*)



(*b*)



(*c*)

Fig. 2

(*a*) - Slide 1 used in subjective tests
(*b*) - Slide 2 used in subjective tests
(*c*) - Slide 3 used in subjective tests

TABLE 2

Subjective Test Results

Mean Impairment Grade (with Standard Error of Mean in Parenthesis)

2A: Luminance Signal Only Quantised (Monochrome Pictures)

		Slide 1	Slide 2	Slide 3	Mean for the three slides
No dither:	7 bits	1·0 (0·00)	1·00 (0·00)	1·00 (0·00)	1·00
	6 bits	1·17 (0·10)	1·11 (0·10)	1·44 (0·18)	1·24
	5 bits	2·87 (0·17)	2·39 (0·33)	4·06 (0·23)	3·11
	4 bits	4·87 (0·21)	5·28 (0·18)	5·39 (0·18)	5·18
With dither:	7 bits	1·11 (0·11)	1·06 (0·04)	1·00 (0·00)	1·06
	6 bits	1·31 (0·16)	1·61 (0·28)	1·38 (0·17)	1·43
	5 bits	2·00 (0·22)	2·22 (0·43)	2·61 (0·33)	2·28
	4 bits	3·94 (0·22)	3·70 (0·31)	4·11 (0·26)	3·93

2B: Colour Difference Signals Only Quantised (Colour Pictures)

		Slide 1	Slide 2	Slide 3	Mean for the three slides
No dither:	7 bits	1·20 (0·08)	1·00 (0·00)	1·00 (0·00)	1·07
	6 bits	1·95 (0·28)	1·15 (0·12)	1·55 (0·22)	1·55
	5 bits	3·25 (0·15)	2·95 (0·20)	3·40 (0·21)	3·20
	4 bits	5·30 (0·21)	4·65 (0·22)	5·20 (0·16)	5·05
With dither:	6 bits	1·20 (0·03)	1·05 (0·05)	1·05 (0·03)	1·10
	5 bits	1·35 (0·15)	1·30 (0·13)	1·50 (0·33)	1·38
	4 bits	2·50 (0·18)	2·00 (0·26)	2·70 (0·31)	2·40
	3 bits	3·95 (0·22)	3·80 (0·21)	3·80 (0·21)	3·85

Three slides were used: they are shown in Fig. 2.

The results of the test are detailed in Table 2, which gives the means and standard errors of the mean of the observed impairment grade for each condition.

4. Discussion of results

4.1. Summary of results

4.1.1. Formal subjective tests

A useful criterion for an acceptable system is that the mean picture impairment grade should be less than 1½ on the EBU 6-point impairment scale. Based on the results of the formal subjective tests undertaken using typical picture material, as given in Table 2, the following conclusions may be drawn:

(i) Without dither the luminance signal required 6 bits and the colour difference signals require between 6 and 7 bits.

(ii) When dither was used the luminance signal required just over 6 bits and the colour difference signals required 5 bits.

4.1.2. Other results

As mentioned in Section 3.2, when critical test signals are used the figures are (for the luminance and colour-difference signals respectively) 9 bits and between 7 and 8 bits without dither and between 6 and 7 bits (for all three signals) with dither.

These results, together with the theoretically estimated parameter values, are shown in Table 3; the theoretical results are included on the basis that contouring effects are the limiting factor when dither is not used, and that when dither is used the quantising noise is subjectively equivalent to random noise.

4.1.3. Comparison of results

Although no overall pattern emerges from Table 3, the following points are noteworthy:

(i) When critical test signals are used the subjective results correlate well with the predicted results; when dither is not used typical pictures require between one and two less bits than the predicted parameter values. This is probably due to the fact that whereas contouring is the most noticeable effect when test (saw-

TABLE 3

Required Number of Bits for Luminance (Y') and Colour Difference (V', U') Signals

Theoretical Predictions:	Y'	(V', U')
(i) Without dither	8·4	7·4
(ii) With dither	5·8	6·0
On Typical Slides:		
(i) Without dither	6	6 – 7
(ii) With dither	6	5
On Critical Test Signals:		
(i) Without dither	9	7 – 8
(ii) With dither	6 – 7	6 – 7

tooth) signals are used, typical pictures tend not to include prominent areas of slowly varying signal.

(ii) Roughly speaking, dither saves one bit.

(iii) Relative to the number of bits required for the colour difference signals the luminance signals require a slightly lower bit-rate than expected without dither and a slightly higher bit-rate with dither.

4.2. Practical system considerations

Several additional factors influence the final choice of parameter values to be used in a practical transmission system; some of these have difference implications for systems with and without dither.

Firstly, it is usual to allow some 'headroom' at the ends of the conversion range when quantising video signals; this is to prevent the occurrence of limiting or possible catastrophic effects when the conversion range is exceeded.

Secondly, the results quoted above, particularly in connection with systems employing dither, are valid only for the sampling frequencies used in the experimental tests (13·3 MHz for Y', 4·43 MHz for V' and U'). Roughly speaking, as the sampling frequency is varied a given amount of quantising noise power is distributed over a different bandwidth (equal to half the sampling frequency); as noise at lower frequencies is more objectionable the signal-to-noise ratio is reduced as the sampling frequency is reduced, the equivalence being approximately 3 dB per halving of the sampling frequency which in turn is equivalent to reducing the number of bits per sample by 0·5. This would be an important consideration if, for example, it were proposed to use sub-Nyquist sampling, particularly for the colour-difference signals V' and U'.

Thirdly, a video signal might be expected to emerge from up to four codecs in tandem nominally unimpaired. If the noise added by an analogue-to-digital conversion is essentially random as is the case when dither is used, then four conversions will have increased the noise power by a factor of four over a single conversion, that is by 6 dB; insofar as the amount of noise added is determined by the number of bits per sample employed, this increase is equivalent to a loss of 1 bit. However, in the situation where dither is not used and where a slight non-linearity might occur in the analogue connection, passage through two or more codecs in tandem could give rise to two levels corresponding to adjacent quantising levels in one coder being requantised two quantising levels apart. This effectively doubles the visibility of contouring on certain areas of pictures; hence an extra bit would be required to obviate this effect for any number of codecs in tandem.

4.3. Recommended parameter values for a Reference Codec

Any recommendation for the number of bits per sample must be based on a compromise between the sets of data in Table 3. A system which would be acceptable for typical pictures and almost acceptable for critical signals would be 7 bits per sample without dither or 6 bits per sample with dither dor each of the three component signals.

When the signal is expected to pass through four codecs in tandem nominally unimpaired then these figures, as mentioned in the previous section should be raised by 1 bit to 8 and 7 bits without and with dither respectively; however it should be borne in mind that any reduction in either the quoted sampling frequencies or in the conversion range (for example to allow the signals some 'headroom') would be at the expense of a slight increase in noise power, unless the number of bits per sample were increased.

These conclusions tie up with those of Devereux[4] who stated that for four codecs in tandem 8 bits per sample would be sufficient when quantising a composite PAL signal only if dither were used; roughly speaking the extra bit required may be accounted for by the fact that the PAL signal has a range (with synchronising pulses) of 1·75 times the range of the Y' signal discussed in this report, which implied that for an equivalent quantising accuracy the PAL signal would require 0·82 more bits than the luminance (Y') signal would.

As mentioned above, 7 bits per sample without dither would not be sufficient if the signals were expected to pass through more than one codec in tandem. The level of source noise that would be sufficient to mask contouring effects, with 7 bits per sample, is about –53 dB; hence if the inherent noise level of a signal source is of this order or greater it may be assumed that it acts as a form of dither signal if the number of bits per sample is 7 or more. It therefore follows that in an environment of a source signal-to-noise ratio of 53 dB unweighted (60 dB weighted) or less, 7 bits per sample would be adequate with or without dither. However, contouring might still be visible in certain areas of the picture (as discussed in Section 4.2) if the source signal-to-noise ratio were higher, for instance with electronically generated signals.

5. Conclusions

The work described in this report was undertaken to ascertain the number of bits per sample required to represent the digital signals in a transmission system employing separate coding of the luminance and colour-difference signals; further work would be necessary to provide estimates of the sampling frequencies required for these signals.

The required number of bits per sample was estimated both by considering the visibility of contouring effects caused by quantising and by equating quantising noise to the allowable random noise level on an analogue transmission link. Subjective tests were also carried out with test signals and with typical slides; as expected test signals were more critical of quantising effects.

The complete set of results is shown in Table 2 for sampling frequencies of 13·3 MHz and 4·43 MHz for the luminance and colour-difference signals, respectively; the results determined by the subjective tests were those conditions which cause an impairment grade of not greater than 1·5 on the EBU 6-point impairment scale. In all cases the number of bits per sample representing each colour-difference signal is taken to be equal. Since the signals are intended to pass through up to four codecs in tandem nominally unimpaired, and bearing in mind the noise levels inherent in normal picture sources it is recommended that the number of bits per sample for each of the three component signals be seven whether or not dither is used. However, in the case of electronically generated signals visible contouring could arise if some form of dither were not used, unless an increased number of bits per sample were used. In addition, any reduction in the sampling frequencies quoted using those parameter values would be at the expense of a slight decrease in the signal-to-noise ratio.

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7. Appendix

7.1. Component coding equations

The equations relating the component-coded signals Y_o', V_o' and U_o' to the source gamma-corrected primary signals R_o', G_o', B_o' are:

$$Y_o' = \mathrm{l}R_o' + \mathrm{m}G_o' + \mathrm{n}B_o'$$

$$V_o' = (1-\mathrm{l})R_o' - \mathrm{m}G_o' - \mathrm{n}B_o' = R_o' - Y_o'$$

$$U_o' = -\mathrm{l}R_o' - \mathrm{m}G_o' + (1-\mathrm{n})B_o' = B_o' - Y_o'$$

where l = 0·299, m = 0·587 and n = 0·114. (l + m + n = 1) and $R_o' = R_o^{1/\gamma}$ etc.

The primary (gamma-corrected) signals at the receiver are derived from the component signals by inverting the above equations thus:

$$R_1' = Y' + V'$$

$$G_1' = Y' - {}^{\mathrm{l}}/_{\mathrm{m}}V' - {}^{\mathrm{n}}/_{\mathrm{m}}U'$$

$$B_1' = Y' + U'.$$

If these signals are fed directly to a display device the displayed primary luminosities are

$$R_1 = (R_1')^{\gamma}$$

However, because of the form of the CCIR viewing conditions (see Section 2.1) a more general case must be considered in which

(i) There is ambient illumination which is added to the displayed light to produce the preceived light.

(ii) There is a finite non-zero luminance produced in the display when the input signals are zero (in the absence of any ambient illumination).

In developing the equations relating the displayed primaries R_d, G_d, B_d to the transmitted signals both additional sources of light are assumed to be 'grey' i.e. to possess equal Red, Green and Blue components.

Taking these conditions in reverse order, the effect of the zero signal luminance (F_o) may be quantified by adding a constant signal E_o to the signals R_1', G_1' and B_1' to produce signals R_2', G_2' and B_2'; these signals may be expressed as

$$R_2' = E_o + \mathrm{k}R_1' \text{ etc.}$$

where k is a constant of proportionality. Since the displayed value of each primary colour is equal to unity at peak signal levels, k = $(1 - E_o)$. The amount of colour produced on the display is

$$R_2 = (R_1')^{\gamma} = (E_o + \mathrm{k}R_1')^{\gamma} \text{ etc.}$$

When the input signal $R_1{}'$ is zero then

$$R_2 = E_o^{\gamma} = F_o \text{ and thus}$$

$$E_o = F_o^{1/\gamma}$$

Adding the ambient light (L_o) yields for the displayed primary luminosities the equations

$$R_d = \left\{E_o + (1 - E_o)\,(Y' + V')\right\}^{\gamma} + L_o$$

$$G_d = \left\{E_o + (1 - E_o)\,(Y' - {}^{l}/_{m}V' - {}^{n}/_{m}U')\right\}^{\gamma} + L_o$$

$$B_d = \left\{E_o + (1 - E_o)\,(Y' + U')\right\}^{\gamma} + L_o$$

7.2. Equivalence of quantising noise and random noise – prediction of required number of bits per sample

In this Appendix the number of bits per sample required to specify the luminance and colour-difference signals is estimated by equating the quantising noise power to the allowable random noise power in a video analogue transmission link.

The allowable random noise levels, relative to the black-to-peak white signal swing, for a composite PAL colour-coded signal are:

(i) Luminance Channel: –52 dB, weighted by an RC low-pass filter of time constant 0·2 μs.

(ii) Chrominance Channel: –46 dB, in the chrominance frequency band.

When quantising noise is random, it is assumed to have a flat frequency spectrum and its total power is $\sigma^2/12$, σ being the quantising step. This means that a signal specified by n bits will have a peak-signal to quantising-noise ratio of

$$(6{\cdot}02\,n + 10{\cdot}8)\ \text{dB}$$

For the luminance signal, –52 dB weighted noise is equivalent to –45·2 dB flat noise (from d.c. to 5·5 MHz). This implies that the required number of bits to specify the luminance signal is 5·71 bits. However, using a sampling frequency of 13·3 MHz and 5·5 MHz low-pass filter at the d.a.c. output reduces the quantising noise by 0·8 dB allowing the signal to be specified by 5·58 bits.

In the chrominance band the allowable weighted random noise is –46 dB relative to 1 Volt;* this is equivalent to –41·8 dB for flat noise across the whole (in Ref. 3, 5·8 MHz wide) video band, in which in turn is –46 dB for flat noise in a bandwidth of ±2·22 MHz (or half sampling frequency in the experimental case).

The composite colour subcarrier is $0{\cdot}493U' \pm 0{\cdot}877V'$: thus the allowable flat-spectrum noise levels relative to their peak-to-peak signals are –44·8 dB for V' and –47·8 dB for U'. Changing both figures to –46 dB would not alter the total noise power and although marginally more wasteful of bits than by allocating equal noise powers to the V' and U' signals, it allows calculations to be made on the basis of an equal number of bits per sample for V' and U'.

Next the effect of the colour-difference signals filters are considered; these will attenuate the flat-spectrum noise by 0·9 dB giving an allowable quantising noise power (relative to the peak-to-peak signal range) of –45·1 dB. Thus the number of bits required to specify the colour difference signals is 5·72 bits.

To ensure that the quantising noise does, in fact, have a noise-like character, a 'dither' signal is generally added to the signal prior to quantising. The amplitude of the dither signal is related to the quantising step and the effect of this signal is to reduce the overall signal-to-noise ratio by 1·50 dB, raising the required number of bits per sample by ¼ bit.

Therefore, when dither is used the required number of bits per sample, on the assumption of a quantising-random noise equivalence become 5·83 bits for Y' and 5·97 bits for U' and V': if the quantising noise is inherently of a random nature then these figures may be relaxed by 0·25 bits, yielding 5·58 bits for Y' and 5·72 bits for U' and V'.

7.3. Contouring effects – prediction of required number of bits per sample

In this appendix we calculate the perceptibility of changes in the displayed luminance and chromaticity relative to small changes in the transmitted component signals Y', V' and U'. The number of quantising levels required for each of the uniformly-quantised signals is then estimated by equating a quantising step to the minimum value of the variation in the signal which gives rise to a luminance or chrominance j.n.d.

In the first part of the appendix several combinations of peak level input primary signals (R_o, G_o, B_o) are chosen; this demonstrates which colours may be expected to be most sensitive subjectively to variations in the Y', V' and U' signals.

Next the effect of varying the signal levels, in the case of the most critical colours, is investigated, and the maximum relative perceptibility is calculated. A value of gamma (γ) of 2·5 is assumed, and the calculations are carried out for CCIR viewing conditions in which

(i) the ambient lighting on the display device is 0·7 cd/m², i.e. 0·01 of the luminance corresponding to peak-white

(ii) the display luminance corresponding to zero input signal is also 0·01 of the peak-white luminance.

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* This is the black-to-peak-white signal range.

7.3.1. Sensitivities of various colours

To obtain the sensitivities of the fractional luminance changes and chromaticity changes to variations in the transmitted component signals the following nine partial derivatives were evaluated for all saturated colour combinations:

$$\frac{\delta \log L_1}{\delta Y'} \qquad \frac{\delta \log L_1}{\delta V'} \qquad \frac{\delta \log L_1}{\delta U'}$$

$$\frac{\delta u_1}{\delta Y'} \qquad \frac{\delta u_1}{\delta V'} \qquad \frac{\delta u_1}{\delta U'}$$

$$\frac{\delta v_1}{\delta U'} \qquad \frac{\delta v_1}{\delta U'} \qquad \frac{\delta v_1}{\delta U'}$$

Source signals in the 'off' state (for example red in the case of cyan) were assigned non-zero values of 0·01; this is to avoid any spurious results when assuming that the gamma-law characteristic is obeyed at very low signal levels.

L_1 is the display luminance, and u_1 and v_1 are display chromaticity co-ordinates respectively. It is easiest to carry out the partial differentiation by using the following modifications of the equations of Section 2.1.

$$R_1 = (V' + Y')^\gamma$$

$$B_1 = (U' + Y')^\gamma$$

$$G_1 = (Y' - {}^{\mathrm{l}}/_{\mathrm{m}}V' - {}^{\mathrm{n}}/_{\mathrm{m}}U')^\gamma$$

$$L_1 = \mathrm{l}R_1 + \mathrm{m}G_1 + \mathrm{n}B_1$$

$$\frac{u_1}{v_1} = 1{\cdot}156\,\frac{(\mathrm{l}R_1)}{L_1} + 0{\cdot}972\,\frac{(\mathrm{n}B_1)}{L_1} + 0{\cdot}198$$

$$\frac{1}{v_1} = 0{\cdot}233\,\frac{(\mathrm{l}R_1)}{L_1} + 5{\cdot}08\,\frac{(\mathrm{n}B_1)}{L_1} + 2{\cdot}61$$

Table 1 shows the values of these quantities, expressed in j.n.d. units, evaluated for various saturated colours. It is evident that

(i) Red and blue are the colours most sensitive to variations in the V' and U' signals respectively;

(ii) Quantising these V' and U' signals results in a change in log L_1 (in terms of j.n.d.'s) greater than the corresponding chromaticity change $\sqrt{(\Delta u_1)^2 + (\Delta v_1)^2}$

(iii) Blue is the colour most sensitive to changes in the Y' signal.

7.3.2. Variation of sensitivity with signal level

As the amplitudes of the input *RGB* signals are reduced, the sensitivities of the displayed luminance and chromaticity to variations in the transmitted (Y', V' and U') signals increase; this is because, for example, fractional changes in luminance increase for a given change in luminance as signal level is decreased. Factors which limit this increase in sensitivity are the ambient light, and the zero signal luminance setting of the display.

The following calculations demonstrate how the maximum sensitivity of the display luminance (expressed as log L_1) caused by a variation in the Y', V' or U' signals may be computed. CCIR viewing conditions are again assumed.

The equations for the displayed luminosities (R_d, G_d, B_d), derived in Section 7.1 are:

$$R_\mathrm{d} = \{E_\mathrm{o} + (1 - E_\mathrm{o})\,(Y' + V')\}^\gamma + L_\mathrm{o}$$

$$G_\mathrm{d} = \{E_\mathrm{o} + (1 - E_\mathrm{o})\,(Y' - {}^{\mathrm{l}}/_{\mathrm{m}}V' - {}^{\mathrm{n}}/_{\mathrm{m}}U')\}^\gamma + L_\mathrm{o}$$

$$B_\mathrm{d} = \{E_\mathrm{o} + (1 - E_\mathrm{o})\,(Y' + U')\}^\gamma + L_\mathrm{o}$$

where L_o is the ambient illumination on the display (assumed 'white', i.e. having equal red, green and blue components); E_o is the display signal level (above zero) under conditions of a zero input signal (R_o, G_o, B_o) level and corresponds to a luminance of the display device if 0·01 of maximum and the normalised value of E_o thus equals

$$(0{\cdot}01)^{1/\gamma} \text{ or } 0{\cdot}158 \text{ for } \gamma = 2{\cdot}5$$

Next those colour combinations which are subjectively most sensitive (at their peak levels) to small changes in each of the transmitted signals are chosen; for each of these combinations (Blue, Red and Blue in the case of Y', V' and U' respectively) the source signal level will be varied to find the value of level which gives rise to the greatest subjective sensitivity with respect to the transmitted signals.

The display luminance is

$$L_\mathrm{d} = \mathrm{l}R_\mathrm{d} + \mathrm{m}G_\mathrm{d} + \mathrm{n}B_\mathrm{d}$$

and the luminance sensitivity to small changes in the Y' signal is

$$\frac{\delta \log L_\mathrm{d}}{\delta Y'} = \frac{1}{L_\mathrm{d}}\,\frac{\delta L_\mathrm{d}}{\delta Y'}$$

From the above equation the expression for $\delta L_\mathrm{d}/\delta Y'$, after substituting for Y', V' and U' becomes, with $R_\mathrm{o} = G_\mathrm{o} = 0$:

$$\frac{\delta L_\mathrm{d}}{\delta Y'} = \gamma(1 - E_\mathrm{o})\,[(1 - n)E_\mathrm{o}^{\gamma - 1} +$$

$$n\{E_\mathrm{o} + (1 - E_\mathrm{o})B_\mathrm{o}{}^{1/\gamma}\}^{\gamma - 1}]$$

Given the parameter values chosen it may be shown that

$$\frac{1}{L_d}\,\frac{\delta L_d}{\delta Y'}\left(\text{or } \frac{\delta \log L_d}{\delta Y'}\right) \text{ which is of the form}$$

$$a\,.\,\frac{b + X^{\gamma-1}}{c + X^{\gamma}}$$ has a maximum value (corresponding to $X = 0{\cdot}19$ or $B_o^{1/\gamma} = 0{\cdot}038$) of 6·672: in j.n.d. units this equals 333·5.

Similar expressions are given rise to when considering variations in the V' and U' signals on Red and Blue source signals respectively:

$$\frac{\delta \log L_d}{\delta V'} \text{ and } \frac{\delta \log L_d}{\delta U'}$$

are found to have maximum values of 2·43 and 1·92 respectively. In j.n.d. terms these figures become 123 and 97.

7.3.3. Number of bits required for Y', V', U'

The number of levels required to represent a uniformly quantised signal is given by multiplying sensitivity (in j.n.d. units) to perturbations in that signals by the peak-to-peak value of that signal. Thus from Section 7.3.2, the number of levels required for Y' is 336 x 1·0 = 336; for V' it is 123 x 1·402 = 172 and for U' it is 97 x 1·778 = 171. These figures correspond to 8·4, 7·4 and 7·4 bits per sample respectively.

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